The XMM deep survey in the CDF-S II. a 9-20 keV selection of heavily obscured active galaxies at z>1.7

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ABSTRACT

We present results on a search of heavily obscured active galaxies $z > 1.7$ using the rest-frame 9-20 keV excess for X-ray sources detected in the deep XMM-CDFS survey. Out of 176 sources selected with the conservative detection criteria ($> 8\sigma$) in the first source catalogue of Ranalli et al., 46 objects lie in the redshift range of interest with the median redshift $\tilde{z} \simeq 2.5$. Their typical rest-frame 10-20 keV luminosity is 10^{44} erg s^{-1}, as observed. Among optically faint objects that lack spectroscopic redshift, four were found to be strongly absorbed X-ray sources, and the enhanced Fe K emission or absorption features in their X-ray spectra were used to obtain X-ray spectroscopic redshifts. Using the X-ray colour-colour diagram based on the rest-frame 3-5 keV, 5-9 keV, and 9-20 keV bands, seven objects were selected for their 9-20 keV excess and were found to be strongly absorbed X-ray sources with column density of $N_{\rm H} \geq 0.6 \times 10^{24}$ cm^{-2}, including two possible Compton thick sources. While they are emitting at quasar luminosity, $\sim 3/4$ of the sample objects are found to be absorbed by $N_{\rm H} > 10^{22}$ cm^{-2}. A comparison with local AGN at the matched luminosity suggests an increasing trend of the absorbed source fraction for high-luminosity AGN towards high redshifts.

**Key words.** X-rays: galaxies - Galaxies: active - Surveys

1. Introduction

A population of heavily obscured Active Galactic Nuclei (AGN) at cosmological distances, which might be missed by conventional quasar surveys, has been postulated by AGN synthesis models of the X-ray background (XRB, e.g., Gilli, Comastri & Hasinger 2007; Treister, Urry & Virani 2009) and the super-massive black hole mass function in the local Universe (Marconi et al 2004). Various infrared selections have been employed extensively for seaching for these objects in which strong re-radiation from obscuring dust is expected (Martínez-Sansigre et al 2005; Alonso-Herrero et al 2006; Daddi et al 2007, Fiore et al 2008, 2009; Bauer et al 2010; Vignali et al 2010; Alexander et al 2011; Luo et al 2011; Donley et al 2012). Although X-ray observations should, in principle, also be effective for the search on account of the intrinsic X-ray loudness of AGN (relative to galaxy emission) and the penetrating power against obscuration, the low throughput of the existing X-ray telescopes limits the accessibility to high redshift. However, dedicated deep surveys with extremely long

exposures, for example, in the Chandra Deep Field South (CDFS) conducted by XMM-Newton (Comastri et al 2011) and Chandra (Giacconi et al 2002; Xue et al 2011) X-ray observatories now allow us to pursue this approach. Here, we present a study of X-ray selected heavily obscured active galaxies using the 3 Ms XMM-Newton survey of CDFS.

X-ray absorption is measured by the low energy cut-off of an X-ray spectrum, which moves to higher energies as absorbing column density increases. When $N_{\rm H}$ approaches 10^{24} cm^{-2}, the cut-off occurs above 10 keV. As demonstrated for nearby examples, such as NGC 4945 (Iwasawa et al 1993), the Circinus Galaxy (Matt et al 1999), and NGC 6240 (Vignati et al 1999), detection of emission above 10 keV plays a key role in discoveries of heavily obscured AGN in those galaxies with absorbing column density exceeding 10^{24} cm^{-2}. This method works as long as the optical depth is not too large, that is, when a source becomes fully Compton thick with $N_{\rm H} \geq 10^{25}$ cm^{-2}, Compton down-scattering suppresses the hard X-rays, leaving only reflected light, as observed in NGC 1068 (e.g., Matt et al 1997). While a direct access is not possible for nearby objects with XMM-Newton, this crucial energy-band is redshifted

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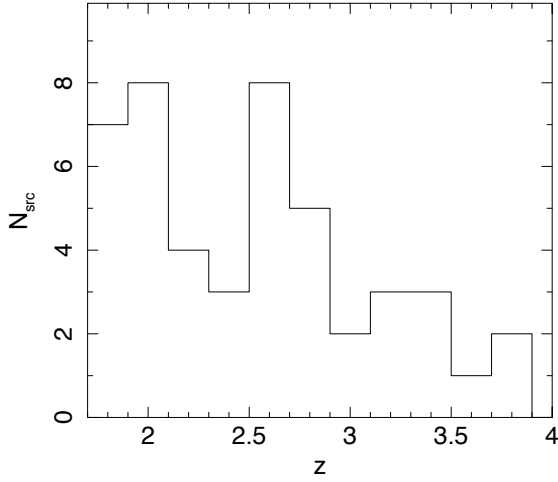
Fig. 1. Distribution of redshifts of the 46 sources in the sample. PID 352 with X-ray determined redshift $z_X = 1.60$ is excluded.
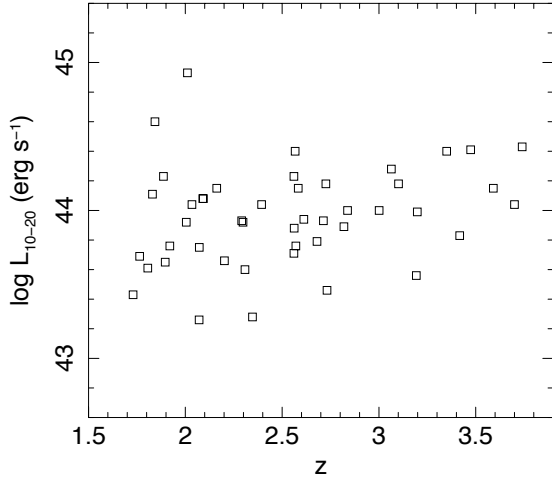
Fig. 2. The distribution of the 46 objects in our sample in the rest-frame 10-20 keV luminosity vs. redshift plane. No correction for internal absorption has been made when calculating the luminosities. The median L_{10-20} is 0.9×10^{44} erg s^{-1}.

into its bandpass for high redshift objects at $z \geq 2$. Given the shape of an absorbed X-ray spectrum, a negative K-correction sustains the detectability of absorbed sources to high redshift. Utilizing these properties, we searched for the rest-frame 9-20 keV excess sources to identify heavily obscured AGN candidates in the sources detected in the XMM-CDFS field.

The cosmology adopted here is $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.72$, $\Omega_M = 0.28$.

2. The Sample

We selected sources from the first XMM-CDFS catalogue with conservative detection criteria: 176 sources that were detected at significance larger than 8σ in the 2-10 keV band and have X-ray spectra verified for use for a spectral analysis are available (details will be described in Ranalli et al in prep.). Since the signal to noise ratio of individual spectra, obtained from the EPIC cameras of XMM-Newton, falls

steeply above 7.5 keV, we set the lower bound of the redshift range of our sample to $z = 1.7$, for which rest-frame 20 keV corresponds to observed-frame 7.4 keV.

There are 47 objects with $z > 1.7$ for which spectral data are available from all the three EPIC cameras, pn, MOS1 and MOS2, apart from two objects which are located outside the field of view of the pn but within the two MOS cameras (see Table 1). Spectroscopic redshifts are available for 33 objects, while photometric redshifts were estimated by various papers (Luo et al 2008; Cardamone et al 2008; Rafferty et al 2011; Wuyts et al 2008; Santini et al 2009; Taylor et al 2009) for other 14 objects[1].

For some objects with photometric redshifts, more constrained redshift estimates could be obtained using the Fe K feature in their X-ray spectra when they have a strongly absorbed X-ray spectrum. We use these X-ray redshifts for five sources (Sect. 3.2). As a result of X-ray redshift determination, one source ($z = 1.60$), which had the original photometric redshift $z = 1.78$, went out of the redshift range. This source (PID 352) is therefore excluded from the sample and will not be discussed further.

Hereafter we use "PID" for the identification number of X-ray sources listed in Ranalli et al, and the basic information of the 46 objects in the sample is presented in Table 1. The redshift distribution of the sample is shown in Fig. 1. The median redshift is $\tilde{z} = 2.5$. The background-corrected counts obtained from the the sum of the three EPIC cameras range from 400 to 8000 in the respective rest-frame 3-20 keV band, while the typical counts are ~ 1400. The typical source fraction of the total (source plus background) counts is $\simeq 0.4$ in both EPIC pn and MOS cameras.

Since the exposure time for each source varies, the observed flux in the observed-frame 1-4 keV band, which is shared by all the sources with various redshifts, is given in Table 1 as an objective measure of source brightness. Median values of the observed frame 1-4 keV flux, f_{1-4}, the rest-frame 2-10 keV and 10-20 keV luminosities, L_{2-10}, and L_{10-20}, are 2.5×10^{-15} erg s^{-1} cm^{-2}, 9.1×10^{43} erg s^{-1}, and 8.7×10^{43} erg s^{-1}, respectively. These luminosities are corrected for the Galactic extinction, $N_H = 9 \times 10^{19}$ cm^{-2}(Dickey & Lockman 1990). Fig. 2 shows how the objects in our sample are distributed in the L_{10-20} - z plane. The spread of the 10-20 keV luminosity is relatively narrow with a logarithmic dispersion of 0.3 (or a factor of ~ 2).

3. Results

3.1. X-ray colour analysis

For selecting sources with various degrees of absorption, three rest-frame energy bands: s (3-5 keV); m (5-9 keV); and h (9-20 keV), are defined and two X-ray colours: s/m and h/m are computed. At energies above 3 keV, little contribution from soft X-ray emission originating from the extranuclear region is expected. As the intrinsic continuum slope in the 3-20 keV band is not expected to vary wildly between objects, absorption would be the main driver of changes in the X-ray colours. For the adopted rest-frame energy range, these X-ray colours are sensitive to column densities larger than $N_H \simeq 10^{22}$ cm^{-2}.

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[1] The photometric redshift adopted in this paper are taken from Ranalli et al., in prep., in which the choices among various photometric redshift estimates are described in detail.

Table 1. Properties of the sample.

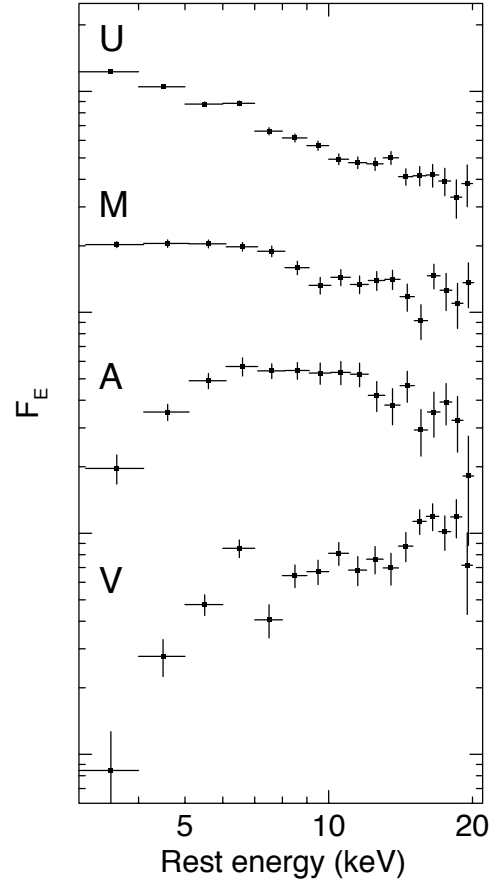| PID (1)	RA (2)	Dec. (3)	z (4)	(5)	(6)	Net (7)	s/m (8)	h/m (9)	(10)	f_{1-4} (11)	L_{2-10} (12)	L_{10-20} (13)
26	53.21484	−27.97884	3.198	sp	a	618	0.35 ± 0.17	0.97 ± 0.33	A	1.7e-15	9.2e+43	9.7e+43
30	53.03737	−27.97493	1.830	x	-	1344	0.29 ± 0.08	2.06 ± 0.27	V	2.5e-15	4.5e+43	1.3e+44
31	53.28854	−27.97376	2.583	sp	a	789	1.03 ± 0.15	1.07 ± 0.19	M	3.9e-15	2.1e+44	1.4e+44
33	53.25708	−27.97188	1.843	sp	a,b	8112	1.20 ± 0.04	0.77 ± 0.05	U	2.5e-14	6.8e+44	4.0e+44
49	52.97654	−27.94723	2.298	sp	c	1474	1.09 ± 0.14	1.07 ± 0.18	M	2.8e-15	1.0e+44	8.4e+43
57	53.29041	−27.93768	2.571	sp	a	1891	1.49 ± 0.14	0.68 ± 0.12	U	2.8e-15	1.8e+44	5.7e+43
62	53.30284	−27.93094	2.561	sp	a	3642	1.40 ± 0.08	0.60 ± 0.07	U	6.1e-15	3.8e+44	1.7e+44
64	53.17001	−27.92967	3.350	x	-	1277	0.23 ± 0.11	1.95 ± 0.31	V	2.5e-15	8.7e+43	2.5e+44
68	53.25377	−27.92238	2.005	sp	d	3023	1.30 ± 0.10	0.75 ± 0.11	U	5.5e-15	2.0e+44	8.4e+43
81	52.93824	−27.90995	1.887	sp	d	5524	1.37 ± 0.07	1.03 ± 0.09	U	1.1e-14	3.1e+44	1.7e+44
84	53.06075	−27.90602	2.561	sp	e	1226	0.99 ± 0.19	1.54 ± 0.31	M	1.3e-15	5.9e+43	5.1e+43
92	53.02137	−27.89840	3.417	ph	f	1066	0.90 ± 0.13	0.91 ± 0.16	M	1.1e-15	9.0e+43	6.7e+43
93	53.00222	−27.89788	2.819	ph	g	995	0.65 ± 0.13	1.05 ± 0.22	M	1.5e-15	7.2e+43	7.7e+43
97	53.19526	−27.89280	2.732	ph	h	441	0.18 ± 0.12	0.75 ± 0.24	A	6.8e-16	3.0e+43	2.9e+43
98	53.01620	−27.89159	3.001	ph	f	1411	0.88 ± 0.13	0.79 ± 0.15	M	1.3e-15	9.3e+43	1.0e+44
103	52.94689	−27.88717	2.034	ph	g	3901	1.17 ± 0.07	0.94 ± 0.08	U	6.4e-15	2.2e+44	1.1e+44
107	52.20927	−27.88088	3.474	sp	c	2468	0.78 ± 0.06	1.01 ± 0.07	M	3.7e-15	2.9e+44	2.6e+44
108	53.05395	−27.87688	2.562	sp	e	1164	0.45 ± 0.06	1.19 ± 0.13	A	1.6e-15	5.7e+43	7.5e+43
114	53.32027	−27.87144	1.806	sp	a	508	0.09 ± 0.20	1.92 ± 0.61	V	1.0e-15	2.2e+43	4.1e+43
116	53.04742	−27.87028	3.740	x	-	2176	0.45 ± 0.05	1.18 ± 0.08	A	3.0e-15	1.9e+44	2.7e+44
120	53.17388	−27.86740	3.591	sp	e	1987	1.24 ± 0.10	0.95 ± 0.09	U	2.1e-15	2.5e+44	1.4e+44
144	53.12423	−27.85159	3.700	sp	e	752	0.29 ± 0.16	1.46 ± 0.33	V	1.0e-15	4.2e+43	1.1e+44
158	52.96872	−27.83828	2.394	sp	e	1331	0.65 ± 0.09	1.34 ± 0.15	M	2.4e-15	8.2e+43	1.1e+44
173	53.18078	−27.82065	1.920	sp	e	2951	1.14 ± 0.07	0.80 ± 0.07	U	3.5e-15	1.1e+44	5.7e+43
180	53.16528	−27.81382	3.064	sp	e	1427	0.22 ± 0.05	2.01 ± 0.18	V	2.2e-15	7.4e+43	1.9e+44
190	53.26092	−27.80650	3.101	ph	f	1965	1.05 ± 0.08	0.87 ± 0.08	M	2.8e-15	2.1e+44	1.5e+44
194	53.03947	−27.80214	2.838	sp	b,e	1464	0.49 ± 0.05	1.03 ± 0.08	A	2.2e-15	1.1e+44	1.0e+44
200	53.24949	−27.79664	2.567	sp	e	6545	1.35 ± 0.05	0.75 ± 0.04	U	8.1e-15	5.1e+44	2.5e+44
201	52.91637	−27.79593	2.713	sp	d	1457	1.42 ± 0.13	0.78 ± 0.11	U	2.6e-15	2.0e+44	8.6e+43
210	53.17847	−27.78400	3.193	sp	e	1106	1.04 ± 0.16	0.69 ± 0.17	M	9.5e-16	8.7e+43	3.6e+43
211	53.03384	−27.78214	2.612	sp	c	1675	1.07 ± 0.10	1.01 ± 0.12	M	2.3e-15	1.1e+44	8.7e+43
213	53.27462	−27.78054	2.202	ph	f	1008	0.92 ± 0.17	0.99 ± 0.25	M	1.4e-15	4.6e+43	4.6e+43
215	53.02193	−27.77877	2.071	sp	c	690	0.12 ± 0.08	0.86 ± 0.16	A	1.1e-15	2.7e+43	4.0e+43
219	52.95665	−27.77598	2.308	sp	d	1042	1.65 ± 0.30	0.96 ± 0.27	U	1.6e-15	7.5e+43	4.0e+43
231	53.09398	−27.76715	1.730	sp	d	1111	0.64 ± 0.09	1.15 ± 0.18	M	1.2e-15	2.4e+43	2.7e+43
245	53.08279	−27.75493	2.680	x	-	373	0.08 ± 0.13	2.23 ± 0.54	V	7.9e-16	2.3e+43	6.1e+43
252	53.08340	−27.74644	1.896	sp	d	441	0.09 ± 0.15	2.44 ± 0.59	V	7.8e-16	1.9e+43	4.5e+43
269	53.37135	−27.73200	1.764	ph	g	663	0.93 ± 0.16	1.20 ± 0.28	M	2.8e-15	5.9e+43	4.9e+43
283	53.10732	−27.71837	2.291	sp	e	2076	0.84 ± 0.08	1.10 ± 0.12	M	2.7e-15	8.7e+43	8.6e+43
285	53.28673	−27.71504	2.072	sp	d	1798	1.37 ± 0.14	0.76 ± 0.15	U	3.3e-15	1.2e+44	5.6e+43
302	53.39597	−27.70256	2.011	sp	a	4054†	1.19 ± 0.05	0.83 ± 0.06	U	4.3e-14	1.4e+45	8.6e+44
311	53.25599	−27.69488	2.091	sp	i	3351	1.08 ± 0.07	1.06 ± 0.10	M	5.7e-15	1.8e+44	1.2e+44
327	53.37052	−27.67841	2.162	sp	d	638	0.74 ± 0.12	0.63 ± 0.16	M	5.0e-15	1.8e+44	1.4e+44
332	53.37428	−27.66908	2.092	sp	d	510†	0.78 ± 0.12	0.51 ± 0.15	M	5.6e-15	1.7e+44	1.2e+44
366	53.07546	−27.61604	2.347	ph	g	882	1.47 ± 0.26	1.37 ± 0.30	U	1.6e-15	7.6e+43	1.9e+43
503	53.00248	−27.72286	2.726	sp	e	2330	0.96 ± 0.06	0.82 ± 0.06	M	3.8e-15	2.3e+44	1.5e+44

Note — (1) Source identification number in the XMM-CDFS catalogue of Ranalli et al; (2),(3) XMM position of source (degrees, J2000); (4) redshift; (5) source of redshift, sp: optical spectroscopic; ph: photometric; x: X-ray spectroscopic; (6) references for the redshift estimates: a: Treister et al (2009b); b: Cooper et al (2011); c: Popesso et al (2009); d: Silverman et al 2010; e: Szokoly et al (2004); f: Luo et al (2008); g: Cardamone et al (2008); h: Rafferty et al (2011); and i: Balestra et al (2010). (7) net counts in the rest-frame 3-20 keV band from all the three EPIC cameras. $\dagger$: MOS1+MOS2 only; (8) X-ray colour, s/m: photon ratio of the rest-frame 3-5 keV and 5-9 keV; (9) X-ray colour, h/m, photon ratio of the rest-frame 9-20 keV and 5-9 keV; (10) X-ray colour category; (11) observed-frame 1-4 keV flux in units of $\mathrm{erg\,s^{-1}\,cm^{-2}}$; (12) rest-frame 2-10 keV luminosity in units of $\mathrm{erg\,s^{-1}}$; (13) rest-frame 10-20 keV luminosity in units of $\mathrm{erg\,s^{-1}}$. The luminosities given here are corrected for the Galactic absorption.

Since our objects have a wide range of redshift (1.7-3.8 in z), these X-ray colours are derived using photon spectra, i.e., spectral data corrected for the detector response and the Galactic absorption as a function of the rest-frame energy. The correction method employed here is practically the same as that used in the XMM-COSMOS spectral stacking analaysis (Iwasawa et al 2012). The photon counts in each band are the weighted mean of the three EPIC cameras, where we adopted the signal-to-noise ratio in the rest-frame 3-20 keV band as the weight. The two X-ray colours, s/m and h/m, for individual sources are listed
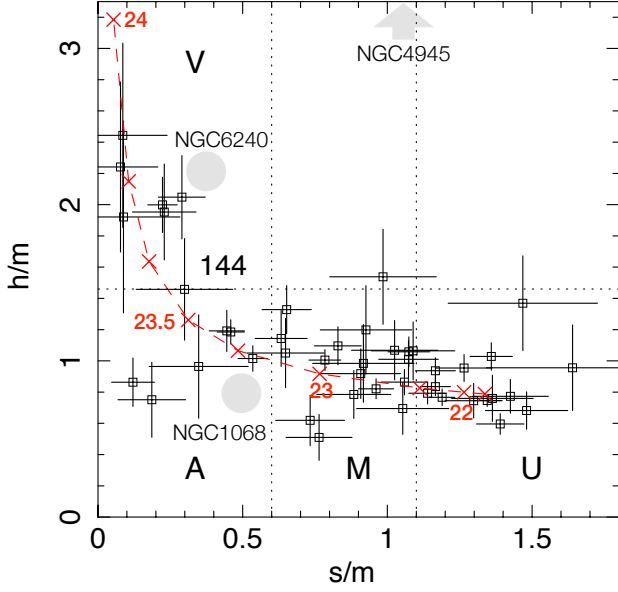
Fig. 3. The X-ray colour-colur diagram, based on the data obtained from the XMM-Newton EPIC cameras, where s, m and h are the detector-response-corrected photon counts in the rest-frame bands of 3-5 keV, 5-9 keV and 9-20 keV, respectively. The four categories, V, A, M and U and their boundaries are indicated. Our reference heavily obscured AGN, PID 144, is labeled in the diagram. The red dashed-line indicates the evolution track of the X-ray colour when a power-law of $\Gamma = 1.8$ is modified by various absorbing colmun. The crosses mark $\log N_{\rm H}$ values 21, 22, 22.5, 23, 23.3, 23.5, 23.7, 23.85 and 24 (cm^{-2}) from the bottom-right to the upper-left along the track. The X-ray colours estimated for the nearby, heavily obscured AGN, NGC 6240, NGC 4945 and NGC 1068 are also plotted. Note that NGC 4945 has a large value of $h/m = 6.8$, which is outside of the frame (see text for details of these sources). X-ray spectra of the two sources (PID 84 and 366) with $h/m \sim 1.4$, located in the M and U intervals, respectively, are described in text (Sect. 3.1).

in Table 1, and the colour-colour diagram is shown in Fig. 3.

With the two X-ray colours, a column density range of $\log N_{\rm H} = 22\text{-}24$ (cm^{-2}) can be probed, as s/m covers the lower $N_{\rm H}$ regime and h/m does the higher. In Fig. 3, a locus of spectral evolution when a power-law continuum of photon index $\Gamma = 1.8$ is modified by various absorbing column of $\log N_{\rm H}$ between 21 and 24 (cm^{-2}) is drawn. As the s/m represents softness of a spectrum below 9 keV, objects at the bottom-right in Fig. 3 are populated by sources with little absorption. The s/m colour moves to the left as absorption increases. Two divisions were made along the s/m axis, at $s/m = 0.6$ and 1.1. In the lowest interval, the model locus turns upwards as increasing absorption at $\log N_{\rm H} \geq 23.5$ (cm^{-2}) and a few sources indeed spread towards higher h/m values, which indicates an excess of 9-20 keV emission.

PID 144 ($z = 3.70$) is a previously known, heavily obscured AGN with an X-ray absorbing column of $N_{\rm H} \sim (0.6\text{-}0.9) \times 10^{24}$ cm^{-2} (Norman et al 2002; Comastri et al 2011), located in this interval. We take this object with $h/m =$

Fig. 4. The rest-frame 3-20 keV stacked spectra for the four categories, defined in Fig. 3. The vertical axis is in arbitrary unit of flux density. Only the XMM-Newton data were used. The spectral stacking is a straight sum of individual sources while a weighted mean of the available EPIC data, based on the signal to noise ratio, is taken for each source. Number of sources, typical redshift and luminosity of each category can be found in Table 2. For a reference, the spectral slope of the U category spectrum is $\alpha \simeq 1.8$, where $F_{\rm E} \propto E^{-\alpha}$, i.e., photon index $\Gamma \simeq 1.8$.

1.46 as the reference and sources that have h/m larger than this object were classified as 9-20 keV excess sources.

According to the three intervals along s/m and two intervals along h/m, four zones, V: Very absorbed; A: Absorbed; M: Modestly absorbed; and U: Unabsorbed, are defined in the colour-colour diagram, as shown in Fig. 3. The degree of absorption thus increases in the order of U, M, A, and V, and typical column densities for these X-ray colour categories would be $\log N_{\rm H}$ of ≤ 22, 22.7, 23.4, and 23.8 (cm^{-2}), respectively.

For a comparison, the X-ray colours of nearby, well-studied heavily obscured AGN, NGC 6240 ($N_{\rm H} \sim 2 \times 10^{24}$ cm^{-2}), NGC 4945 ($N_{\rm H} \sim 5 \times 10^{24}$ cm^{-2}), and NGC 1068 ($N_{\rm H} \geq 10^{25}$ cm^{-2}) were computed, based on the spectra presented in Vignati et al (1999), Guainazzi et al (2002), and Matt et al (1997), respectively, obtained from the BeppoSAX observations (see Fig. 3). In these low luminosity systems, non AGN components, e.g., a circumnuclear starburst, flaring X-ray binaries (e.g., Brandt, Iwasawa & Reynolds 1996), can make a significant contribution to their spectra in the lower energy range, altering the s/m colour

Table 2. Properties of the four X-ray colour categories, V, A, M, and U.

Category (1)	N (2)	$\tilde{z}$ (3)	$\log \tilde{L}_{2-10}$ (4)	$\log \tilde{L}_{10-20}$ (5)	Γ_{10-20} (6)
V	7	2.68	43.59	44.04	0.3 ± 0.2
A	6	2.78	43.86	43.93	1.5 ± 0.3
M	19	2.56	43.96	43.93	1.3 ± 0.2
U	14	2.19	44.20	43.99	1.6 ± 0.1

Note — (1) The X-ray colour category (see Fig. 3); (2) Number of objects belonging to the category; (3) Median redshift; (4) Median rest-frame 2-10 keV luminosity; (5) Median rest-frame 10-20 keV luminosity; (6) Photon index in the 10-20 keV band of the stacked spectrum (see Fig. 3). Photon index Γ is related to the energy index α, where flux density, $F_E \propto E^{-\alpha}$, by $\Gamma = \alpha + 1$.

Table 3. X-ray redshift measurements.

PID	z_X	Photo-z
30	1.83 ± 0.07	$2.123^a, 1.936^b, 1.84^c, 1.683^d$
64	3.35 ± 0.04	$3.528^a, 3.341^c, 3.301^e$
116	3.74 ± 0.06	$3.53^a, 3.99^b, 4.63^f, 4.14^g$
245	2.68 ± 0.12	$3.001^a, 2.431^h, 2.28^k$
352	1.60 ± 0.02	1.78^d

Note — z_X is the X-ray spectroscopic redshift with 1σ error. The Fe K features are assumed to arise from cold matter (see text for details).
References for photometric redshifts a: Luo et al (2008); b: Cardamone et al (2008); c: Rafferty et al (2011); d: Taylor et al (2009); e: Wuyts et al (2008); f: Wardlow et al (2011); g: Wardlow et al (2011, the second solution); h: Dahlen et al (2010); k: Santini et al (2009).

in particular, more than in high luminosity AGN like our sample. Despite of this spectral complexity, h/m serves as a good indicator of strongly absorption seen in sources like NGC 6240 and NGC 4945. The h/m colour moves back to a lower value for a fully Compton thick source, e.g., NGC 1068, but it still remains in a zone of hard spectrum sources.

Two sources, PID 84 and PID 366, have h/m values similar to the reference PID 144 but softer s/m colours (see Table 1). An inspection of their spectra shows that PID 84 has a moderately absorbed spectrum with $N_H \simeq 1 \times 10^{23}$ cm^{-2} as expected for the M category, while PID 366 in the U interval shows a relatively soft spectrum but with a deficit at the rest-frame 7-10 keV (observed 2.2-3 keV range), causing the large value of h/m. This could be attributed to a strong Fe K edge caused by absorption of $N_H \sim 6 \times 10^{23}$ cm^{-2}, where a spectral complexity might play a role to mask the strong absorption.

The sources in the V and A categories are absorbed by N_H of a few times of 10^{23} cm^{-2} or larger, so that prominent Fe K features in the form of an emission line or an absorption edge can be observed. This offers a possibility to derive a reliable X-ray spectroscopic redshift. There are five objects in the two categories with only photometric redshifts. X-ray redshift (z_X) were obtained for these five objects and their X-ray colours were recomputed assuming the new redshifts. Details of the X-ray redshift measurements are described in Sect. 3.2.

Basic information on the sources in the four categories is given in Table 2 and their stacked, rest-frame 3-20 keV spectra are shown in Fig. 4, which demonstrates representative spectral shapes for respective categories. Note that exceptionally hard 10-20 keV spectrum of V compared to the other three, indicating that large absorption column ($N_H \sim 10^{24}$ cm^{-2}) are affecting the sources in this category (Table 2).

3.2. X-ray redshift measurements

Redshift was measured with X-ray spectra for five objects, PID 30, 64, 116, 245, and 352, which have only photometric redshifts (Table 3). These objects are too faint in the optical band to obtain a reliable spectroscopic redshift. The photometric redshifts reported by various authors for each object spread over a significant range, while they can serve as a guide for a redshift range to be searched in. The Fe K

features imprinted in their absorbed spectra gave improved accuracy in the redshift measurements. The Chandra data from the 4 Ms (Xue et al 2011) and the ECDFS (Lehmer et al 2005) observations were also added to the analysis for improving the spectral quality. The observed-frame 0.5-7 keV spectra of these sources are shown in Fig. 5, except for PID 352, details of which will be reported in a separate paper. They are photon spectra combining XMM-Newton and Chandra data for displaying purpose only. All the spectral results presented hereafter were obtained by fitting spectral datasets from different cameras jointly.

The redshift determination was principally driven by the Fe K edge, which is assumed to arise from cold medium and thus at the energy of 7.1 keV, as it is normally statistically more robust feature than the line. Two exceptions are PID 116 and PID 352, for which the Fe K emission-lines, detected at 2.5σ with EW ≈ 0.15 keV and 4.5σ with EW ≈ 0.30 keV, respectively, were used to obtain the redshifts assuming the rest-frame line energy of 6.4 keV emitted from cold matter.

This assumption may not be true for PID 116, which is a luminous submillimetre galaxy detected at 870 μm with LABOCA (LESS 9, Wardlow et al 2011; Biggs et al 2011). As the X-ray detected luminous infrared galaxies with $L_{IR} \sim 10^{13} L_\odot$ at $z > 2$ in the COSMOS field appears to show high-ionization Fe K emission, e.g., Fe XXV at 6.70 keV and/or Fe XXVI at 6.97 keV as inferred from a spectral stacking analysis (Iwasawa et al 2012), the emission line of PID 116 could also be either of these high-ionization lines. In this case, the redshift would be $z = 3.96$ or $z = 4.16$, when it was identified with Fe XXV and Fe XXVI, respectively. The former value is close to the photometric redshift derived by Luo et al (2008) and the latter to the secondary solution of Wardlow et al (2011) (see Table 3).

As shown in Table 3, z_X are found to lie within the range of various photometric redshifts.

3.3. 9-20 keV excess sources

The spectra of the seven objects in the V category are shown in Fig. 5 and 6. For displaying purpose, EPIC pn, EPIC MOS1, MOS2, and the Chandra data from the ACIS detector are combined together. All the spectra show spectral discontinuities at 6-7 keV, indicating an Fe K line
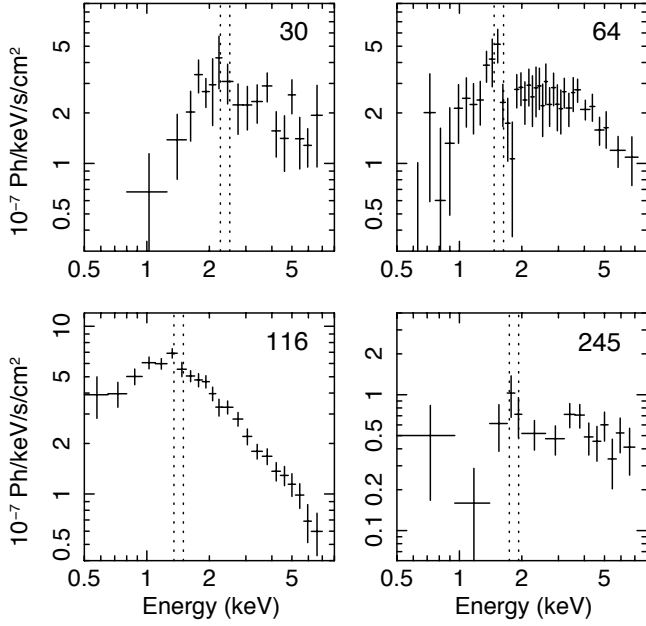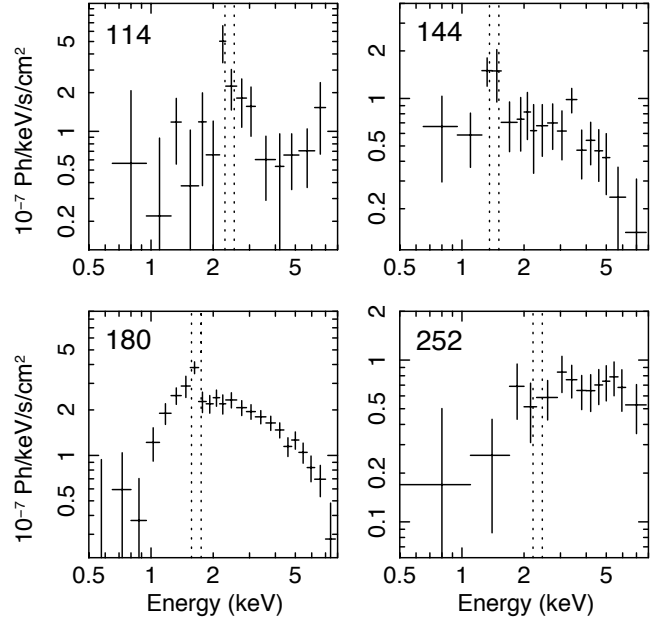
Fig. 5. The X-ray spectra of the four objects (PID 30, 64, 116, 245) whose redshifts were determined using the Fe K features. The Chandra ACIS-I data, obtained in the deep CDFS (4 Ms) and the ECDFS observations, were combined with the XMM-Newton data. The rest-frame 6.4 keV and 7.1 keV which would be observed with those redshifts are indicated by the dotted lines. PID 30, 64, and 245 are heavily obscured sources in the V category while PID 116 is a source in the A category.

and/or a deep Fe K absorption edge, in agreement with strong absorption.

To estimate the absorbing column density of these sources, an absorbed power-law model with photon index of $\Gamma = 1.8$ is fitted (Table 4). The absorption model with the Wisconsin cross section (Morrison & McCammon 1983) and the one with the effects of Compton scattering taken into account, PLCABS (Yaqoob 1997), give consistent results on N_H. Whilst the absorption cut-off is slightly modified when Compton scattering is taken into account, the 7-20 keV spectrum, shaped by an Fe K edge, remains unchanged in shape for the N_H range of our sources, $N_H \leq 10^{24} \mathrm{cm}^{-2}$, (although the flux is further suppressed). This also applies to recently developed more sophisticated X-ray spectral models (e.g., Ikeda, Awaki & Terashima 2009; Murphy & Yaqoob 2010). As our N_H fits are mainly driven by the data in the Fe K edge band, it can be understood that both absorption models gives similar N_H, given the data quality of the spectra. However, since Compton scattering reduces the continuum level further compared to the case where the scattering effect is not taken into account, the absorption correction factor for estimating an intrinsic continuum luminosity would be larger. This effect also depends on the geometry of the absorber (e.g., Matt et al 1999) which is not known for our objects. In Table 4, we give absorption-correction factors for a spherical absorber. These factors could go up by a factor of ~ 2 as the covering factors decreases down to that of a disk-like geometry for the relevant range of N_H.

The column densities given in Table 4 were obtained, assuming the observed emission is transmitted light through

Fig. 6. The X-ray spectra of the four objects (PID 114, 144, 180, 252) which complete the seven objects of the V category in addition to the three objects shown in Fig. 5. The rest-frame 6.4 keV and 7.1 keV are indicated by the dotted lines that were computed assuming the spectroscopic redshifts for respective objects.

Table 4. X-ray absorption in the 9-20 keV excess sources.

PID (1)	$N_{H,24}$ (2)	AC_{2-10} (3)	AC_{10-20} (4)
30	$0.57^{+0.07}_{-0.06}$	7	1.5
64	$0.83^{+0.05}_{-0.04}$	12	1.9
114[†]	$0.40^{+0.15}_{-0.10}$	4	1.3
144	$0.81^{+0.06}_{-0.06}$	11	1.9
180	$0.55^{+0.03}_{-0.02}$	6	1.5
245	$0.96^{+0.09}_{-0.08}$	15	2.1
252[†]	$0.97^{+0.11}_{-0.09}$	16	2.1

(1) Source identification number; (2) Absorption column density in unit of 10^{24} cm^{-2}; (3) Absorption correction factor for the 2-10 keV luminosity; (4) Absorption correction factor for the 10-20 keV luminosity.
Note — Spectral fits were performed for the observed-frame 1-7 keV data using an absorbed power-law with $\Gamma = 1.8$. When a Thomson opacity approaches unity, as observed in these sources, the absorption correction depends on the geometry of absorbing clouds (e.g., Matt et al 1999). In this table, the values for a spherical geometry are given as the lower limits. These values can go up by a factor of ~ 2, as the covering factor of the absorber is reduced. †: The spectra of these sources can also be described well by a reflection spectrum from cold matter.

an absorber. However, the hard X-ray colour exhibited by these objects could also result from a reflection-dominated spectrum of a Compton thick source. This is probably the case for PID 114, in which a strong Fe K line is detected (see below and Table 5), whereas the apparently moderate column density is inferred from the absorption model for the poor quality continuum spectrum (Table 4). PID

Table 5. Fe K line equivalent widths of the V category objects.

PID	EW$_1$ keV	EW$_2$ keV
30	0.76 ± 0.24	0.51 ± 0.19
64	0.57 ± 0.19	0.27 ± 0.11
114	1.40 ± 0.61	1.09 ± 0.53
144	1.13 ± 0.51	0.47 ± 0.23
180	0.65 ± 0.16	0.34 ± 0.12
245	1.10 ± 0.48	0.44 ± 0.28
252	≤ 0.5	≤ 0.2

Note — EW$_1$ and EW$_2$ are measured with respect to the rest-frame 5-10 keV continuum modelled by a simple power-law and an absorbed power-law of $\Gamma = 1.8$, respectively. For PID 252, 2σ upper limits are given. We remark that EW$_2$ are always smaller than EW$_1$ since part of the line is accounted for by the sharp continuum feature of an absorbed continuum carved by an Fe K edge.

Fig. 7. The distribution of absorbing column density N_{H}, obtained by fitting an absorbed power-law to the EPIC spectra. The lowest bin represents the number of objects with no detection of absorption. The typical error bar of each bin is ± 1.

252 has the hardest spectrum in terms of the hard X-ray colour h/m (Fig. 6) although no obvious Fe line is seen. For these two objects, a pure reflection spectrum from cold matter, modelled by `pexrav` (Magdziarz & Zdziarski 1995) or `pexmon` (Nandra et al 2007), provides a comparable fit to their spectra, compared to the absorption model. This indicates that these two objects might be Compton thick AGN with a larger N_{H} than that given in Table 4, e.g., $\sim 10^{25}$ cm^{-2}.

Fe K emission is detected at $\sim 2\sigma$ or larger significance in these objects except for PID 252 (Table 5, see also Comastri et al 2011). The spectrum of PID 252 does not show clear Fe K emission with EW ≤ 0.5 keV (2σ upper limit of a narrow line at 6.4 keV). This weak-line source may be a high-redshift analogue of Mrk 231, a Compton thick AGN with a weak Fe K line in the local Universe (e.g., Braito et al 2004; Gallagher et al 2002; Iwasawa et al 2011 and other references therein). The large EW observed in PID 114 (Table 5) agrees with an Fe K line expected from a reflection-dominated spectrum from cold medium, giving a support to the possibility of a Compton thick source.

4. Discussion

4.1. X-ray selection of heavily obscured AGN

Seven heavily obscured active galaxies with $N_{\mathrm{H}} \geq 0.6 \times 10^{24}$ cm^{-2}, including one previously known source (PID 144, Norman et al 2002; Comastri et al 2011), were selected by the rest-frame X-ray colour selection, primarily utilizing the excess emission in the 9-20 keV band relative to emission at lower energies. Two of them (PID 114 and PID 252) are possibly Compton thick AGN with a reflection-dominated spectrum. Given the limited bandpass available from XMM-Newton, this selection can be applied only for high redshift objects, but the a posteriori checks showed that this selection is reliable for sources with spectra of reasonable quality, and can pick up strongly absorbed sources with near Thomson-thick opacity.

This method is a pure X-ray selection, and these seven objects compose a sample of heavily obscured, moderate-luminosity quasars with $L_{10-20} \sim 10^{44}$ erg s^{-1}, selected by
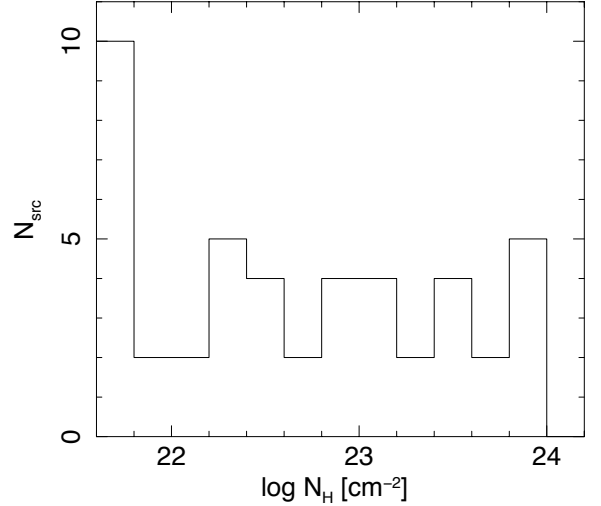
the hard X-ray emission above 10 keV beyond the local Universe.

There are various reports in the literature on Compton thick AGN candidates in the CDFS using whole or part of the Chandra 4 Ms data (e.g., Norman et al 2002; Mainieri et al 2005; Tozzi et al 2006; Fiore et al 2008; Gilli et al 2011; Feruglio et al 2011; Luo et al 2011; Brightman & Ueda 2012; Fiore et al 2012). Some of them lie in the redshift range of our sample, although they are expectedly faint and just a few of them entered in our sample of relatively bright sources. Fiore et al (2012) investigated high-redshift sources at $z > 3$ in CDFS and selected several heavily obscured AGN. Their E537 (=PID 245), M5390 (=PID 144), M8273 (PID 180), M3320 (=PID107) and M4302 (=PID 120) are in our sample. Our results on the spectra of these sources agree except for PID 120 for which only moderate absorption of $N_{\mathrm{H}} = 1.6^{+0.5}_{-0.6} \times 10^{22}$ cm^{-2} is found. The smaller N_{H} value for PID 245 obtained by us (Table 4) is explained by the lower redshift adopted for this source: the X-ray redshift $z_{\mathrm{X}} = 2.68$ (Sect. 3.2, Table 3), instead of the photometric redshift $z = 4.29$ from the GOODS-ERS (Grazian et al 2011) adopted by Fiore et al (2012), which a close inspection of the X-ray/optical/infrared images suggests to be the redshift for another galaxy near the X-ray source.

4.2. Absorbed AGN fraction

In Fig. 3, when the model locus is used as a guide, 10 objects appear to have *unobscured* X-ray sources, i.e., their X-ray absorption is $N_{\mathrm{H}} < 10^{22}$ cm^{-2}. That is, $\sim 3/4$ of our sample objects host significantly obscured active nuclei. Fitting to the individual spectra verifies the above assessment with 12 objects having N_{H} values smaller than 10^{22} cm^{-2}, and gives the N_{H} distribution shown in Fig. 7. The distribution of logN_{H} (cm^{-2}) is nearly flat between 22-24, although the two objects (PID 114 and 252) possibly move up to log $N_{\mathrm{H}} > 24$ (cm^{-2}). For their typical 2-10 keV intrinsic luminosities [$(0.8-5)\times 10^{44}$ erg s^{-1}], these active galaxies

at $z \sim 2.5$ can all be considered to emit at quasar luminosity, and 74 ± 8 per cent of them are absorbed X-ray sources. We have estimated this absorbed AGN fraction using a Bayesian approach and the binomial distribution (Wall & Jenkins 2008) with a 68 per cent confidence interval (S. Andreon, priv. comm.). It should be noted that, since the fraction of Compton thick AGN is not constrained, this value is considered to be the lower limit of the absorbed AGN fraction.

We compared our findings with the predictions of the XRB synthesis model by Gilli et al (2007). Our sample spans the 2-10 keV flux range $(2\text{-}54)\times 10^{-15}$ erg cm^{-2} s^{-1}. Since the sensitivity of the XMM-CDFS observations strongly varies across the field, we computed the model predictions at the 2-10 keV limiting flux, $f_{2-10}^{lim} = 4 \times 10^{-15}$ erg cm^{-2} s^{-1}, which returns the same AGN surface density of our sample, i.e. 46 sources at $z > 1.7$ distributed over a ~ 0.27 deg^2 area. The predicted obscured fraction (defined as the number of AGN with $\log N_{\rm H} > 22$ over the total number of AGN in the sample) is 0.54 ± 0.06, smaller than the observed value of 0.74 ± 0.08.

In the local Universe, the SWIFT/BAT and INTEGRAL surveys show that absorbed sources (with $N_{\rm H} > 10^{22}$ cm^{-2}) consist ~ 55 per cent of hard X-ray selected AGN (e.g., Burlon et al 2011 and references therein). It is also found that this fraction depends on X-ray luminosity, and at the luminosity matched to our sample, the fraction is 21 ± 8 per cent (Burlon et al 2011, see also Ebrero et al 2008). The absorbed quasar fraction ($L_{2-10}^{\rm int} \geq 10^{44}$ erg s^{-1}) in our sample is higher than that of the local Universe, suggesting a positive evolution with redshift, as found in the previous work by La Franca et al (2005), Treister & Urry (2006) and Ebrero et al (2008). No evolution of the obscured AGN fraction was assumed in Gilli et al (2007), yet the prediction comes close to the observation at $z > 1.7$ as discussed above. However, we note that the luminosity dependence of the obscured AGN fraction assumed in Gilli et al (2007) appears to be shallower than the observations (Hasinger 2008; Brusa et al 2010; Burlon et al 2011), and it overestimates the obscured fraction of QSOs with $L_{2-10} > 10^{44}$ erg s^{-1} in the local Universe by a factor of ~ 2.5. This excess number assumed for local obscured QSOs then compensates the lack of a redshift evolution of their fraction in the model.

Contrary to the high-luminosity AGN, no strong evidence for a redshift dependence of the obscured AGN fraction at luminosities $< 10^{44}$ erg s^{-1} has been found. Gilli et al. (2010), for instance, showed that the increasing trend of the absorbed fraction *as observed* by Hasinger (2008) for AGN with $L_{2-10} \leq 10^{44}$ erg s^{-1}, can be accounted for by the K-correction effect, and is instead consistent with a non-evolving *intrinsic* absorbed fraction. Here we suggest that the obscured fraction increases with redshift *only* for luminous QSOs. The different behaviours in obscured fraction between low- and high-luminosity AGN may reflect their distinct accretion mechanisms, as argued in literature (Hasinger 2008; Hopkins et al 2008; Hickox et al 2009): merger-driven accretion for luminous AGN (e.g., Menci et al 2008) and secular accretion for less luminous AGN, possibly mirroring their respective drivers of star formation (e.g., Elbaz et al 2011). This may not be the whole story but qualitatively explains the different bahaviours between AGN of the low and high luminosity ranges. If all QSOs originate from a major merger of gas-rich galaxies (e.g.,

Sanders et al 1988), the increase of merger rate at high redshift (with $\propto (1+z)^2$, e.g., Xu et al 2012) naturally sees an increase in number of QSOs. A merger causes gas channelling to the nuclear region (Barnes & Hernquist 1991). This concentration of gas and the chaotic geometry left by a merger would lead to a high probability of the nuclear region to be seen obscured (e.g., Hopkins et al 2006, but see Shawinski et al 2012) until the radiation pressure of the buried QSO sweeps it away. In the context of this evolutionary scenario alone, the obscured fraction of QSOs is expected to be constant at all redshift, given the short duration of the QSO lifetime ($\leq 10^8$ yr, Hopkins et al 2005). The evolution we observed is probably driven by the increase in the gas fraction of a galaxy towards high redshift (e.g., Carilli et al 2011), combined with the efficient inflow induced by a merger. A higher gas fraction of merger progenitor galaxies means more gas to be transported to the nuclear region to form heavier obscuration. This would result in a longer duration of the obscured phase, which can be translated to a higher obscured fraction of the QSO population at high redshift. At the same time, the elevated gas density by a merger increases the efficiency of star formation leading to a starburst (e.g., Barnes & Hernquist 1991, Elbaz et al 2011). Kinetic energy injection from a starburst may help to maintain the obscuration by inflating gaseous wall around AGN (e.g., Fabian et al 1998). Conversely, the lack of mergers may explain the little evolution of the obscured fraction in lower luminosity AGN. The gas fraction of galaxies hosting them also increases towards high redshift in the same way as for high-luminosity AGN. However, without a major merger, the gas reservoir is not transported to the nuclear region rapidly. This means that the nuclear obscuration condition remains little affected regardless the amount of gas contained in a galaxy (hence redshifts). The gas content is instead consumed to form stars over galaxy-wide as a secular process, and the feeding to the black hole from a large-scale disk remains relatively inefficient.

In summary, we present a result of a rest-frame 9-20 keV selection of heavily obscured AGN at $z > 1.7$, using the deep XMM-CDFS survey, and also show that the fraction of absorbed AGN at high luminosity may be higher at high redshift than in the local Universe. In the near future, a further advance in this area of research will benefit from even deeper observations of deep fields with Chandra and XMM-Newton, while NuSTAR and Astro-H which will provide us with useful templates and insights at lower redshifts. It is also useful to standardize various X-ray spectral models of strongly absorbed systems with improved physics incorporated for the community to share with.

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